LUNAR ROTATIONAL DISSIPATION IN SOLID BODY AND CORE. J. G. Williams , X X Newhall, C. F. Yoder, and J. O. Dickey, Jet Propulsion Laboratory, California Institute of Technology, Pasadena, CA, 91109

Analyses of Lunar Laser Ranging (LLR) observations of the Moon's three-dimensional rotation (physical librations) indicates that the dissipation acting on lunar rotation is surprisingly large for a period of one month [1]. The LLR computations for dissipation have been based on a solid-body tidal dissipation model. An additional model is now implemented which allows for dissipation at a liquid-core/solid-mantle interface. Also, for the solid-body tides the dependence of dissipation on period is explored. Tidal dissipation at one year is weakly detected and roughly half of the monthly dissipation could be due to turbulent core/mantle interaction (core radius 300 km).

Tides on the Moon have long been evident in the LLR analyses from their influence on the lunar rotation. The Love number k_2 is well determined through the rotation [1] and now even the Love number h_2 is barely detected through the tidal displacement of the reflectors. Dissipation by solid-body tides is an expected process and has been part of the LLR analysis model. That model uses tides with a constant time delay for each tidal component (Q is inversely proportional to frequency, dissipation is proportional to k_2/Q). With the assumption that solid-body tides act alone, [1] gives Q = 26.5 ± 1.0 at a one month period.

The existence of a liquid lunar core is a question of long standing. If it exists, then dissipation at the core/mantle boundary is expected. The large size of the observed lunar dissipation has been cited [1] [2] as evidence consistent with, but not proving, a liquid core. A core dissipation model has been implemented in the LLR analysis software. To the large gravitational torques acting on the mantle is added a small additional torque $\underline{T}$

$$\underline{T} = K\,(\,\underline{\omega}_c - \underline{\omega}_m\,) \qquad (1)$$

where $\underline{\omega}_c$ and $\underline{\omega}_m$ are vector angular velocities of the core and mantle, respectively, and K is a dissipation parameter (the ratio of K to the moment C is to be fit). The core/mantle boundary is taken as spherical so the only torque on the core is $-\underline{T}$. The equations of rotation for the mantle and core are numerically integrated along with the equations of motion for the orbits of the Moon and planets. Partial derivatives with respect to K/C, the two initial angular velocity vectors, two sets of initial Euler angles, two moment of inertia differences, gravitational harmonics, k_2, and tidal dissipation are also integrated so that solutions can be made.

The lunar equator (mantle) is tilted I = 1.54° to the ecliptic plane and it precesses with an 18.6 yr period. For the expected weak coupling between the core and mantle, the core's equator should be tilted to the ecliptic plane by a few arc minutes and should precess with the same 18.6 yr period. The direction of the two angular velocity vectors in eq. (1) will be 1.5° apart and the difference will rotate in 18.6 yr in space. For a 300 km radius core, the maximum speed difference at the core/mantle interface is R ω sin I = 2 cm/sec. The torque law of eq. (1) is appropriate for either viscous or turbulent interaction. Turbulence is expected [2].

The equator and orbit planes precess along the ecliptic plane with the same 18.6 yr (retrograde) period. In the absence of dissipation the descending node of the equator matches the ascending node of the orbit. The most important effect of dissipation on the lunar rotation is a phase shift of the precessing equator plane (and pole of rotation) [1] [2]. Dissipation from both solid-body tides and core/mantle interactions can cause this effect. The observed dissipation shifts the pole of rotation by 0.26" (2 m for the lunar radius) and it is strongly observed in the LLR data. This shift gives the dissipation at a one month period. The separation of different sources of dissipation and the determination of Qs at tidal periods other than a month requires distinguishing much smaller signatures at different periods.

Dissipation due to a core would cause little observable effect except the phase shift of the precession. Tidal dissipation in the Moon causes four smaller, potentially observable periodicities in addition to the precession phase shift [3]. In longitude libration there are terms with periods of 206 d, 1 yr, and 3 yr (1095 d). The 206 d term is mainly sensitive to monthly tides. The annual term is sensitive to annual tides. The 3 yr term is mainly sensitive to monthly and 3 yr tides. The latitude libration has a 6 yr term which is more sensitive to monthly tides, but has some sensitivity at 6 yr. Of the four terms the annual term is the most promising for detection with the existing range data. It is orthogonal (cosine) to the large conventional annual term (sine) due to the triaxial lunar figure and is little affected by uncertainties in third-degree harmonics. The 3 yr term is large and may be useful in the future, but it is close to the 1056 d free libration in longitude [4] and much more sensitive to third-degree harmonics.

Several fits to the Lunar Laser Range data were made. a) A solution using only solid-body tides gives Q = 26 for one month. b) A solution with solid-body tides (Q inversely proportional to frequency) and core dissipation attributes about half of the monthly effect to each (solid-body Q = 55). c) A solution for the 1 and 3 yr terms in addition to tidal and core dissipation gives 0.0043" ± 0.0025" for the annual term. This is equivalent to Q = 60 at 1 yr (uncertainty range 35 to 150). The core dissipation is now slightly more important than solid-body dissipation at a month (solid-body Q = 65), but the ability to separate them weakens. For dissipation due to turbulent interaction [2] a core with the density of iron would have a 300 km radius. d) When the dissipation terms are forced to give the same Q for all periods, the resulting solid-body Q is 59.

It is also possible to investigate the dissipation at the 2.9 yr (1056 d) free libration period. Eckhardt [5] concluded that the free libration in longitude could have been stimulated by resonance passage and that assertion is confirmed [4]. Some dissipation at 2.9 yr is necessary to damp the resonance-passage-induced free libration amplitude down to its present observed value.

Solid-body dissipation appears to be detected at one year. Between one month and one year the consequent variation of Q with frequency is modest, more so than our nominal model (1/frequency). The variation of mantle Q with frequency influences the fit for dissipation due to a core. In addition to tides, interaction at a fluid-core/solid-mantle boundary remains a viable explanation for part of the strong monthly dissipation.

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